Design Practice - 2
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Lecture - 19
Introduction to Actuators

Hello and welcome to this Design Practice 2 module 19. This module will be dedicated to the sensors and actuators design. But before going ahead we will finish some of the things which were left over from the previous run about oxidation process and how you calculate the oxide thickness based on the information about the different molar ratios as well as the density of the oxide as well as the normal silicon.

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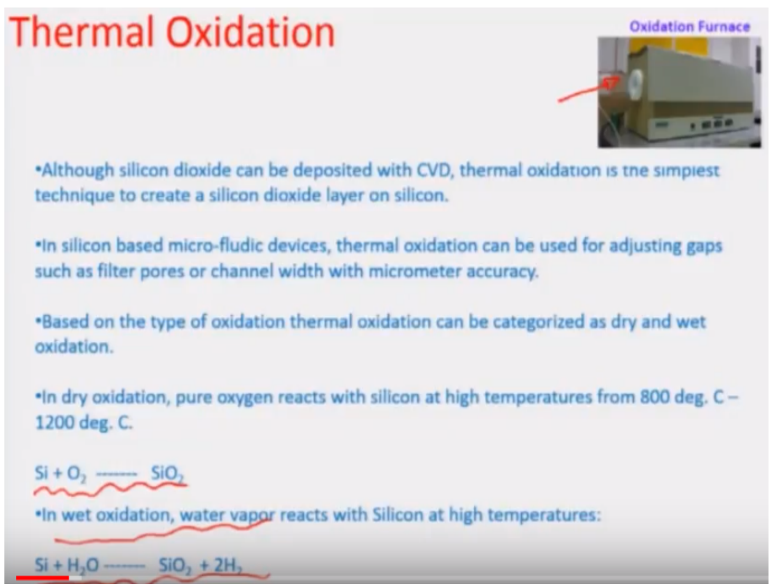

So if we recall, the thermal oxidation is a process where there is a stacking of the wafers inside furnace which is typically a high temperature furnace. The temperature can go as high as about 1200 degree Celsius. And in the meantime there is a flow of oxygen which is made to happen through a quartz tube where these wafers are stacked.

And the oxygen kind of diffuses into the silicon micro structure thus having interstitial oxygen sides and one can record these as SiO2 being formulated. Further the oxidation can be dry or wet if you may recall in the wet oxidation case there is a vapour through which or there is a small bottle trap through which, which is heated up, through which the oxygen is flown so that you have enough moisture content in the oxygen and the reaction is a lot faster.

So we are trying to now, we will try to now estimate the you know the consumption pattern behind the silicon oxide given a certain thickness of silicon and also some other conditions like the molecular density of the silicon, the volume fraction, so on so forth.

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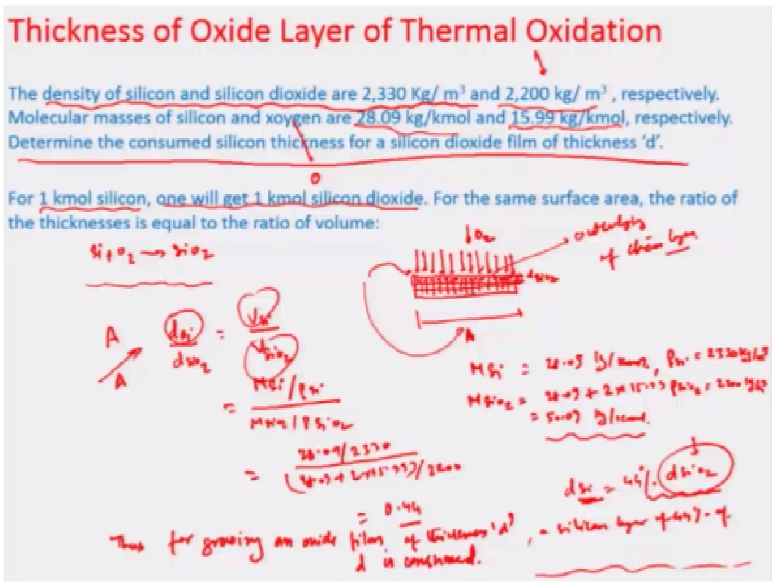

So the density of silicon and silicon dioxide, this particular case had given as 2.330 kg per meter cube and 2.200 kg per meter cube and it is further given that the molecular masses of silicon and oxygen are 28.09 kg/kmol and 15.99 kg/kmol respectively. You want to determine the consumed silicon thickness for the silicon dioxide film of thickness d. So one must remember that this is a perfect 1:1 equation for this stoichiometric ratios 1:1 for silicon oxygen and creates 1 mole of SiO2.

So therefore 1 kmol of silicon and 1 kmol of silicon dioxide would be exactly reaction components. So 1 kmol of silicon and 1 kmol of oxygen together will be on the reactant side and will produce 1 kmol of silicon dioxide on the product side. If we considered a wafer like this where there is going to be a diffusion of the silicon starting top end the area really where the silicon dioxide diffuses and later on the oxide grows.

So the oxide would be based on the penetration and the percolation of the oxygen. So let us say there is a layer thickness of d which has been arrived at because of such percolation and penetration, let us say if we wanted to build up the cross sectional view of the cubic lattice of the silicon we are talking about interstitial impurities of oxygen getting into the lattice structure because of bond vibration and also thermal energy, high thermal energy.

So these are the oxygen moieties being trapped within the crystal. Oxygen is being diffused inside. So if you wanted to estimate what is going to be the d Si, we must look at what is the d SiO2 and for a same area, let us say the surface area in this particular case is given by the area A. So the volume of the silicon on the surface vis a vis the volume of the silicon dioxide is proportional to the depth that the silicon would have and the silicon dioxide would have.

So let us say at the behest of d silicon thickness you obtain the d SiO2 thickness okay and so therefore this ratio is nothing but equal to the volume of the silicon as opposed to the volume of the silicon oxide because the area multiplier is same for both the silicon and silicon dioxide. We do not assume much out bulging okay of the crystal which may otherwise happen. But in this particular case, we assume a 1-dimensional problem and we have similar area whether it is the post diffused or pre-diffused structure of silicon.

So this volume ratio can again be represented in terms of the total mass per unit the density of the silicon and similarly the total mass per unit the density of the SiO2. And let us find out or try to find out what is the total mass of Similarly,. So obviously the total mass of Si as given here is 28.09 kg/kmol and the density of the silicon rho Si is given out to be 2.330 kg per meter cube and similarly the total mass of SiO2 this particular case would be equal to exactly a molar silicon and one molar oxygen.

So the oxygen O has total amount of molecular mass of 15.99 kg/kmol which means SiO2 contains 2 moles of oxygen. So 2 into 15.99 and this becomes equal to the molecular mass of SiO2. The density of SiO2 be again 2.200 kg per meter cube as has been illustrated at about here. So this comes to closely about 50.09 kg/kmol of the material. So having said that the total amount of ratios of the silicon depth and the silicon dioxide is exactly equal to 28.09 by 2330 divided by 28.09 plus 2 into 15.99 divided by 2200.

You know that mass per unit density is the volume. So that is exactly the volume ratio and this becomes equal to about 44% meaning thereby that the amount of silicon that is really consumed is 44% of the SiO2 thickness which comes out which is obvious because there is going to be out bulging of these layers because of the interstitial nature of the oxygen effect and so therefore the layers kind of go out exactly 44 you know by consuming at least thickness which is equal to the 44% of the final bulged out thickness of the silicon dioxide material.

Thus for growing an oxide film of thickness d, a silicon layer of 44% of d is consumed. So this kind of completes the fabrication process in totality. We have had a look at several silicon and polymer processes and systems related to how MEMS are fabricated. The next obvious diversion that we want to take is to study in a specific manner about sensor design and actuator design.

You already have learnt the basic definitions of sensors and modeled some of the sensors like the human eye or the human nose but what is lacking is how in a engineering manner or in a engineering way you can design such sensors and actuators. So let us look at some definitions again. This is a kind of revisiting of what we did earlier. So what is really an actuator and how different it is from a sensor.

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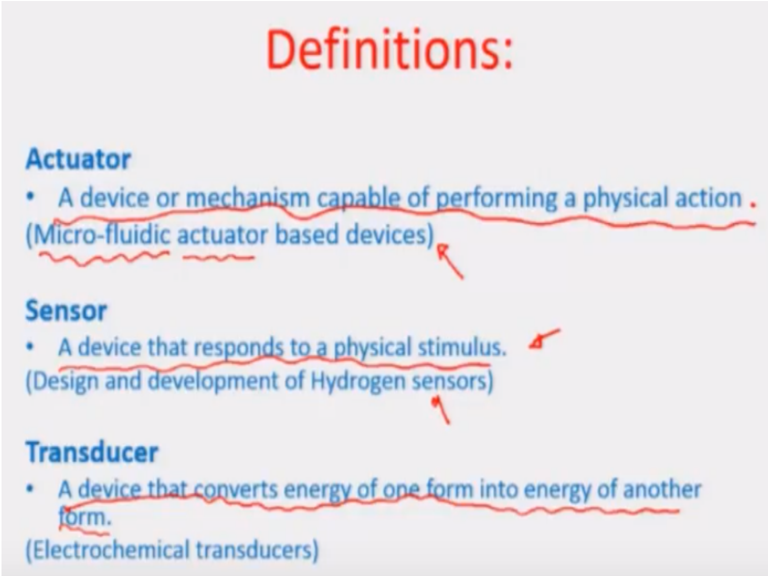

So an actuator is a device or mechanism which is capable of performing a physical action. So this can be in terms of let us say there is a valve and the valve is closed and because of which there is a stoppage of flow. So that can be an actuator. Similarly, there can be initiation of a few membranes because of which there is a travelling contractile effect created and it leads to the increase in the flow velocity because of such a travelling contractile effect.

So these can be again an actuator. So such actuators are used in unison for many purposes and one of the very critical purposes that they are deployed to is you know controlling and defining the flow behavior at the microscopic length scale and this whole area again is known as microfluidics and there are several actuator which are designed based on different device technologies that are there for assisting the flow at the microscopic length scale you may be able to block or valve the flow. You may be able to flow it around a certain path length.

You may be able to mix the flows together. But these controlled, these are done in a controlled manner and the control is all carried out by actuator. So what we are going to learn here is some designs because you know we have to practically be able to design or practically be able to make the generic design of a particular sensor and what I would like to really point out to the audience here is that look at the interdisciplinary flavor of how the design process is carried out.

You need to have learnings from variety of different fields of life including chemistry or physics or even to some extent electronics so that you could realize such an actuator or such a sensor. Similarly, the sensor is a device that responds to a physical stimulus. You have already seen how physical, chemical, and biochemical stimulus stimuli are being responded to by different sensing elements.

In this particular context we will probably look at the design and developments of some hydrogen sensor where we will talk briefly about how a gas sensing film is able to do its job by change of electrical properties when it absorbs the gas and how it can release the gas as soon as the concentration falls down. So there we will use some design principles to design the sensor and then we will also talk about transducers which is which are you know typically devices that convert energy of one form into energy in the other form.

For example there could be an electrochemical transducer which may work on monitoring the pH of a particular biofluid and as a function of the change of pH it is recorded in terms of a voltage signal. So such kind of change of signal processes together can form you know useful device technology and we would like to illustrate some electrochemical transducers in our model. So in the next about 3 to 4 spanning lectures we are going to cover these areas on an aspect of how you design them.

And designing means engineering designing including layout of dimensions, parts etc. so that you are aware of how such actuators and sensors are designed. So let us look into first the microflow side of the story and how that can be controlled and that can be guided.

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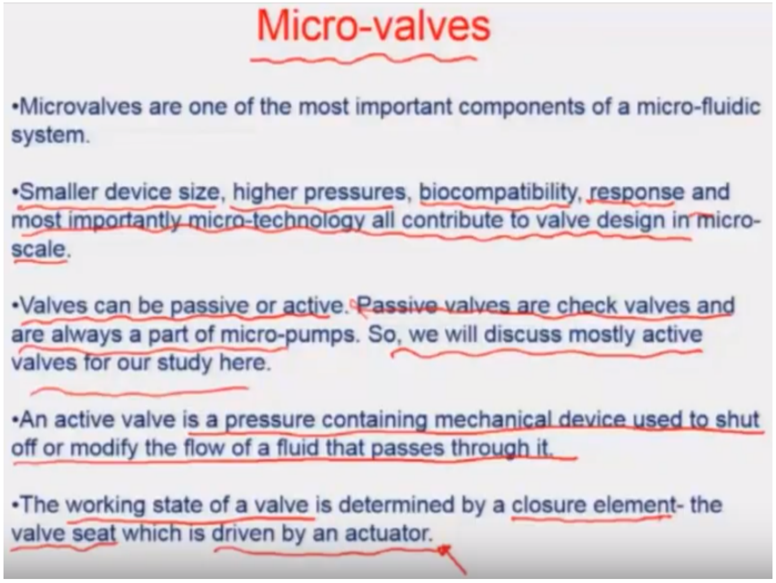

So the first instance which comes to our mind when we talk about actuators are microvalves okay. They are very important for maintaining microscopic flow. There are smaller device sizes when we talk about such microvalves there are challenges like very high pressures. With small sizes and higher pressures you are able to block the flow in such a normal condition so that the design really has to be very robust.

There is also an issue of sometimes biocompatibility because microvalves and microflows are typically used for diagnostic industries and they find a lot of applications. So there are biofluids and whenever there are biofluids there is a question of interaction with the surface across which such fluids would flow. Then there is also a question of what is the rapidity of response whether it is very fast, whether it is able to actuate block, is it analog control or a digital control.

So these aspects are again discussed and most importantly the microtechnology that is involved in contributing to the overall valve designing in the microscale is again another very important aspect of microvalves. So valves can be categorized into being a active or passive. So in fact all actuators are active. All passive actuators passive valves can be check valves okay and they are always a part of pumping systems.

So we are going to discuss extensively the active valves which are energized and they do the job of blocking the flow off. So an active valve really is a pressure containing mechanical device which is used to shut off or modify the flow of a fluid that passes through it and in this kind of a circumstance typically the working state of a valve is dependent on the position of the closure element and the valve seat you know which is actually the closure element is driven through an actuator of some sort which is based on variety of physical principles.

We are going to look into the design aspects of 2 different such principles. One is the pneumatic design and another is a thermo pneumatic design of an actuator which would contribute to microvalving of the flows at that particular length scale.

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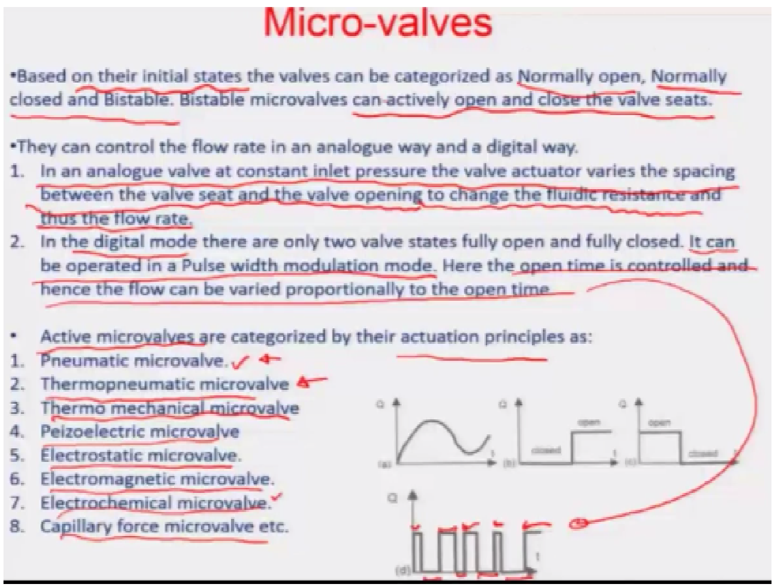

So when we talk about such a valve design and when we discuss about how what are the engineering guidelines which are associated with microvalves. There are various aspects based on which the classification can be carried out for different microvalves. So there is one aspect which talks about mostly the initial states in which the valves are in. They can be categorized as either normally open valves or normally closed valves or a bistable valve.

Meaning thereby that if it is a normally open valve it does not let the flow pass by when it is actuated or otherwise it is open to a flow path and if it is a normally closed valve then in the normal sense the valve will block the flow but when you are actuating the mechanism through which the valving or the valve seat is mechanically being moved you open the valve when the energy is given into the mechanism which moves the valve seat.

There can also be bistable microvalves which could actively open and close the valve seat and so therefore this is in general the categorization of the microvalve actuators. So obviously the control of the flow rate that would happen because of the operation of such a microvalve would be either in a digital manner. All of a sudden stopping the flow by coming into picture or in a analog manner where there is a slow flow behavior as the valve goes from its open position to the close position.

So both have different aspects or different perspectives through which design can be carried out. So in a analog valve at constant inlet pressure, the valve actuator varies the spacing between the valve seat and the valve opening in a continuous manner to change the resistance to the fluid flow and thus the flow rate drops down in a gradual manner making this an analog response of the particular valve.

However, there can be particularly at the microscale, digital microvalves which work in a mode where there is either a normal or normally open position or a normal close position and if it is a normally close position then the valve is supposed to stop the flow or block the flow automatically and it happens within almost at instant so that there are no rates of transient or rates of variation of the properties associated with this particular valve.

So it can be operated in a pulse width modulation mode where there is either an open position for the valve or a close position with a little bit time delay with as little as possible time delay between the open and the close positions. Here of course the open time is controlled and hence the flow can be varied proportionally so you can see a signal for this kind of a microvalve leading to the pulse width modulation activity where there is a concept of duty cycle where the actuation is taking place.

And there is also a concept of a part of the cycle where there is no actuation okay. So really we can optimize this particular pulse width modulation signal in a manner so that it is able to respond in terms of fluid delivery by opening and closing at different frequencies and different lengths of time. So in general the microvalves, the active microvalves can be categorized by the principles through which they operate, through which they actuate.

So it can either be a pneumatic microvalve. We are going to design one such microvalve in the later on section or it can be a thermopneumatic microvalve which is based on a cylinder where there is a air confinement and there is a fixed volume and an increase in temperature so that there is a increase in the pressure within the cylinder because of the fixed volume conditions and this pressure would further result in bending of a cantilever or a switch which because of the actuation would block the particular flow by coming into its path.

Then there are of course thermopneumatic thermo mechanical microvalves so are piezoelectric microvalves, electrostatic microvalves, electromagnetic microvalves, electrochemical microvalves and capillary force microvalves. We will probably see one or two of those cases and try to study that how the engineering design of such valves can come off. But before going into the engineering design aspect, obviously an actuator is the cause for all this to happen.

So therefore the overall valve performance has to be routed in terms of how the actuator is going to work okay for closing up or opening up the valves at different conditions of time and flow rates.

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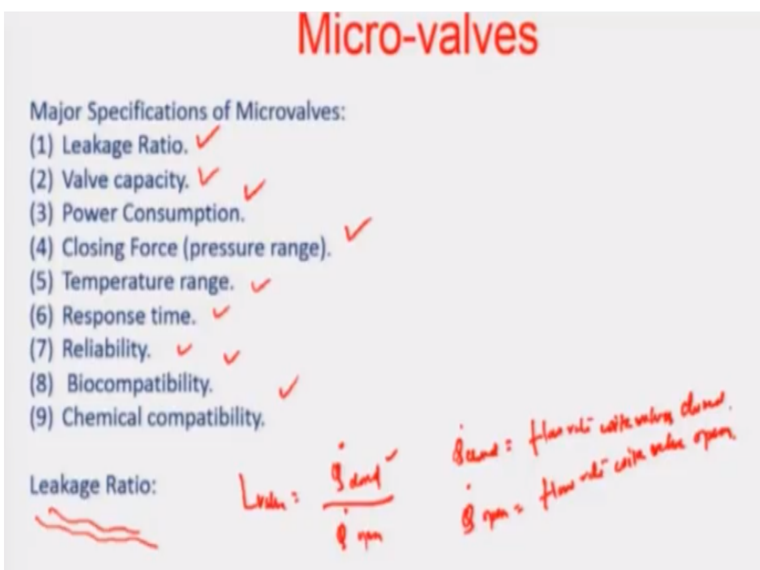

So major specifications in case of valves which we arrive at are the leakage ratio, the valve capacity, power consumption, closing force, temperature range, response time, reliability, biocompatibility and chemical compatibility. So the leakage ratio here for example Lvalve can be given as a ratio between the rate of flow when the valve is in its closed position per unit the rate of flow when the valve is in the open position.

So I will just write this all down that Q dot closed is the flow rate with valve closed and Q dot open is the flow rate with valve open. That is how we define the flows. So flow rate with valve open. So that is how you define the leakage ratio and obviously if the valve is closed this total amount of flow rate could be as miniscule as 0 whereas the opening flow rate with some finite value because of which we can quickly think of a preliminary design of the microvalves based on what is the range of its operation.

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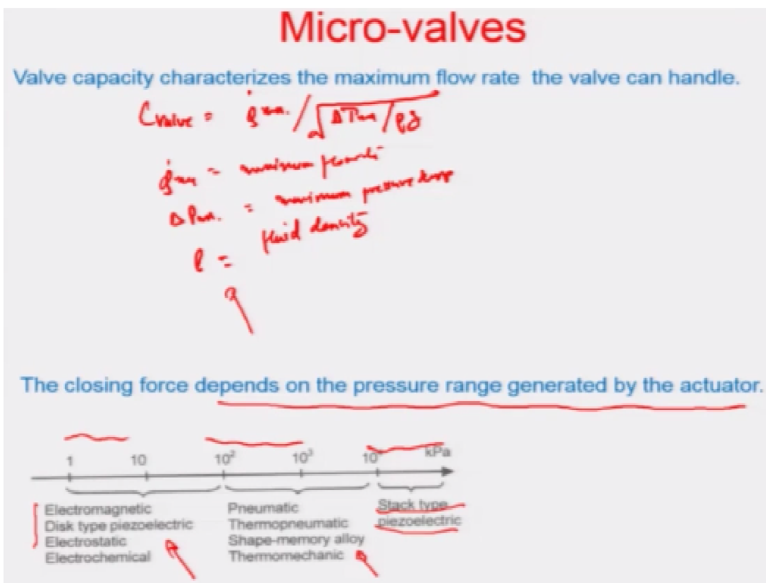

The other important issue is the valve capacity which is actually defined. So there is a mathematical description of this. So it is basically the rate of the maximum flow that the valve can withstand divided by root of the total pressure difference across which the valve is operating per unit the density of the fluid and the you know acceleration due to gravity product. So here the Q dot max is actually the maximum flow rate being able to be allowed from the or through the valve.

And delta P max is the maximum pressure drop from one end to the other of the particular valve across which the flow may be imitating even though the valve is closed, small flows maybe initiating and rho is basically the fluid density which is the one which is getting transported and stopped and blocked by the concerned valve in question. So when we look at what are the kind of forces that are needed to do this closure so that you know the total amount of maximum flow rate reduces after the valve is in the close position.

So that depends on what are the kind of ranges generated by different actuators in terms of their base pressure level. There can be this very high pressurized or very high pressure stack type piezoelectric sensors which would be generating some actuation or there can be relatively low pressure, pneumatic, thermopneumatic shape memory alloy based options base thermomechanic.

And then there can yet be another kind of actuation principle which includes electromagnetic actuation principle, piezoelectric actuation principle, electrostatic and electrochemical. So if there were a need to do a valve design which is more related to you know real time feedback and also the actuator can be made to control from outside based on the feedback that it provides. So you would have to go for one of these types which are compatible with control system and electronics.

So the pressure ranges are given for the various domains okay in this category which we will be handling when we design our microvalves.

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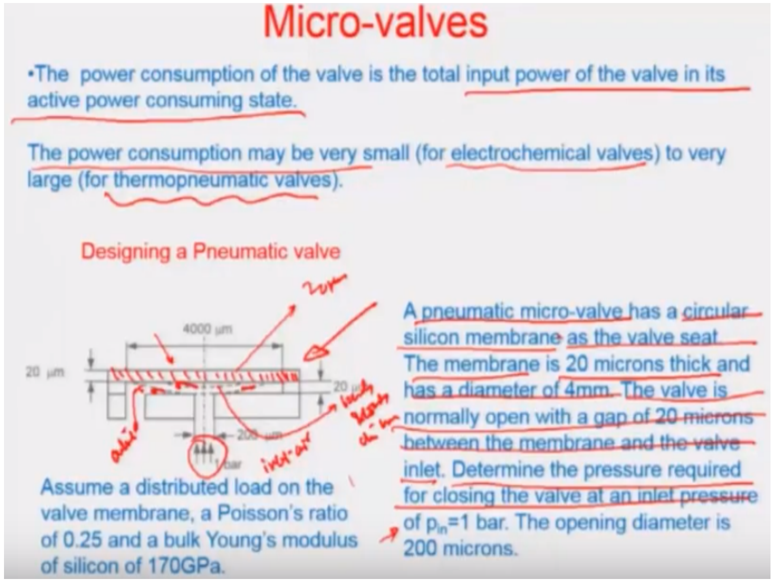

So the power consumption of the valve is the total input power of the valve in its active power consuming state and the power consumption may be very small when we come to very nonconventional forms of actuation like the electrochemical valves for example to very large when it comes to heat mediated pressure development through which there is bending of the member. This right here is an example of a pneumatic valve, what it can do.

So you can see that if I looked at the way that air passes through this whole structure the air enters at one bar from below and it then starts flowing off in both directions and particularly the valve, the branching towards the left here when we are talking about this airflow getting branched into the left side here escapes okay and so the idea is that if I wanted to stop the inlet air to go into the outlet side we need to do something with this member right here which is hashed.

And we need to make sure that this member bends and touches just as it is shown in the dotted line here. So it bends and touches okay the base so that it can cut off the air passage from the inlet to the outlet side. So we want to design a pneumatic microvalve, pneumatic actuation process for this. Some dimensions and some characteristic geometric representations are given. It is a circular silicon membrane which is used as the valve seat and the membrane thickness that we are talking about here for example is only about 20 microns and has a diameter of 4 mm.

The valve is normally open with a gap of 20 microns between the membrane and the valve inlet. And from all this information we will have to determine and design the pressure required for closing the valve at an inlet pressure of p inlet is equal to 1 bar through the process of bending this particular member okay and the opening diameter for the same is about 200 microns. So I am going to solve this numerical problem in the next module.

In the interest of time I am going to close on this particular module. In module 20 we will do the remaining part of this problem followed by another very interesting problem on thermopneumatic microvalves. Till and until then goodbye and thank you.